Spatial and Velocity clumping in an SDSS blue horizontal branch star catalogue

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ABSTRACT

We present evidence for eight new clumps of blue horizontal branch (BHB) stars discovered in a catalogue of these stars compiled from the Sloan Digital Sky Survey (SDSS) by Sirko et al. published in 2004. Clumps are identified by selecting pairs of stars separated by distances $\leqslant$ 2 kpc and with differences in galactocentric radial velocities < 25 km/s. Each clump contains four or more stars. Four of the clumps have supporting evidence: two of them also contain overdensities of RR Lyrae stars which makes their reality very likely. At least one of the clumps is likely to be associated with the tidal debris of the Sagittarius dwarf spheroidal galaxy. We emphasize that more accurate observations of the radial velocities or proper motions of the stars in the clumps as well as the identification of other halo stars in these regions are required to establish the reality of the remaining clumps.

Key words: Galaxy: halo – Galaxy: structure – Galaxy: stellar content – galaxies: individual (Sagittarius) – stars: horizontal branch – stars: RR Lyrae

1 INTRODUCTION

Hierarchical models of galaxy formation predict that clumps and streams should be commonplace in galactic halos. Studies of such structures can give crucial information on the accretion history and formation of our Galactic halo. Compelling evidence for this came with the discovery of the disrupted Sagittarius (Sgr) dwarf (dSph) galaxy (Ibata, Gilmore & Irwin 1994) and its extensive associated stream (e.g. Majewski, 2003 and references therein). On a smaller scale, structure has been found as a "tidal stream" associated with the disintegrating globular cluster Pal. 5. This structure is not smooth but clumpy (Odenkirchen et al. 2003, Grillmair & Dionatos 2006). The origin of this clumping (as a relic of 'disk shocking') has been discussed by Combes et al. (1999), Dehnen et al. (2004) and Capuzzo-Dolcetta et al. (2005).

On a still smaller scale, groups of kinematically associated halo stars have been found by Sommer-Larsen & Christensen (1987), Doinidis & Beers (1989), Arnold & Gilmore (1992), Côté et al. (1993), Majewski, Munn & Hawley (1994), Kinman et al. (1996), Helmi et al., (1999), Kundu et al. (2002), Kinman, Saha & Pier (2004) and Clewley et al. (2005). Recently, Duffau et al. (2006) have found a group containing both RR Lyrae and blue horizontal branch (BHB) stars that they call 'The Virgo Stellar Stream' (hereafter VSS). This feature also coincides with an overdensity of F-type main-sequence stars (Newberg et al. 2002). Gould (2003) on the other hand, analysed a large sample of subdwarfs that lie within 300 pc of the Sun and concluded that not more than 5% of these stars could be in any one kinematic group. A good review of the problems involved in detecting tidal debris in the Galactic halo has been given by Harding et al. (2001).

Blue horizontal branch (BHB) stars are well known tracers of the field star halo. There is presently only one large well selected survey for halo objects (Sirko et al. 2004) that we can use to discover halo structure in both position and velocity space. We therefore use the 1170 BHB star candidates given in Table 3 of Sirko et al. (2004) to search for these small kinematically-associated groups. We restrict our search to the 703 stars with $g \leqslant 18$ in order to increase the probability that the candidates are BHB stars. The distribution of this sample is shown in Fig. 1.

In section 2 we apply our selection technique to the rediscovery of the VSS; we conclude that clumps that we find could well be chance groupings unless there is additional evidence to support their reality. In section 3 we use these methods to identify eight new clumps in the catalogue of SDSS BHB stars given by Sirko et al. (2004). We discuss four clumps of BHB stars where there is additional evidence

that they are real and mention four more where this evidence is lacking. Finally we discuss desiderata for the discovery of more such clumps and the need for a better understanding of their association with globular clusters and dSph galaxies.

2   TECHNIQUES FOR FINDING STREAMS

Our search program takes the galactic coordinates (l, b), the distance (D) and the galactocentric velocity (ν_{los}) for each star from Table 3 of Sirko et al. (2004) and calculates the heliocentric X, Y and Z coordinates for each star [1]. The distance between each star and the others in the catalogue is calculated and only those pairs for which this distance is equal or less than 2 kpc and for which the difference in galactocentric radial velocity (ν_{los}) is less than 25 km/s are retained. These distance and velocity differences were chosen with the aim of identifying kinematically cold groups of stars out to 30 kpc where the distance errors are a few percent and the error in ν_{los} is about 25 km/s. We describe such sets of stars as being *paired*; there are 221 such *pairs* of stars in our sample. For the remainder of this paper we shall refer to this method as the Stellar Pair Search (SPS) technique.

The VSS contains 8 QUEST RR Lyrae stars (from Vivas et al., 2004) and 5 BHB stars from the SDSS catalogue (Sirko et al., 2004). Its validity depends upon the coincidence of the galactocentric radial velocities of its RR Lyrae stars and of the spatial coincidence of overdensities of both RR Lyrae and BHB stars. Only one of the 221 SPS *pairs* belongs to the VSS and so it is clear that such low density clumps would not be easily detected in the BHB catalogue by the SPS method. The principle reason for this is that we are primarily limited by the accuracy of the velocities in the BHB sample. We are therefore forced by the accuracy of the velocities to use inter-star distance as a discriminant which means that we will not find the lower density streams or structures for which BHB stars are not prominent (like the VSS or the Pal 5 stream). We therefore concentrate on finding higher density clumps by considering stars as clump members if they are *paired* with at least *two* other members. We further define a clump as having at least two *pairs* of connected stars. There are eight such clumps in the SDSS catalogue (each having at least four members) which are listed in Table 1 and we discuss in detail in the following section. In an attempt to understand the limitations of the SPS technique we first investigate the probability that these clumps occur entirely by chance.

2.1   The reliability of the technique

Harding et al. (2001) suggested that the presence of clumps can be detected from the lack of normality of the velocity distribution using the W-statistic of Shapiro & Wilk (1965). The probability level ($L_{2.0}$) has been calculated for all the BHB stars within 2.0 kpc of the centroid of each clump and is given in the last column of Table 1. It should be emphasized that this statistic is quite sensitive to the size of the sample. Thus, in the case of clump 1, $L_{2.0}$ is 0.40, but if we had
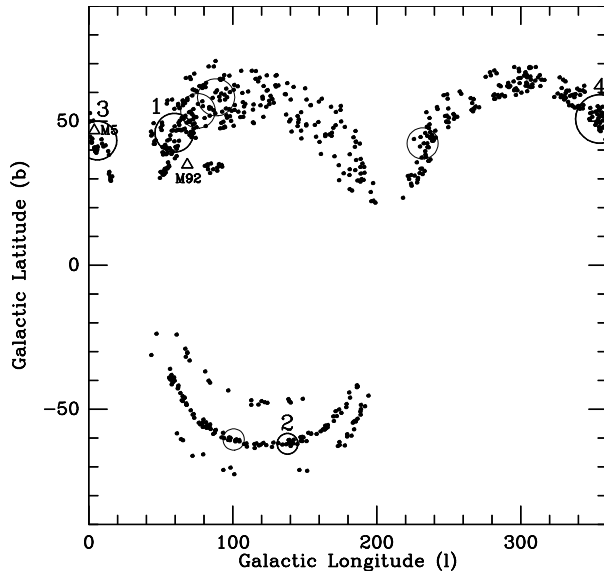

Figure 1. Galactic coordinates for 703 BHB stars with $g \leqslant 18$ from Sirko et al. (2004). Circles are the location of the eight clumps. Bold numbered circles are the locations of the four clumps that have additional evidence that supports their reality. The triangles are globular clusters.

taken the stars within 1 kpc of the centroid the probability level would be 0.08 (a 1 in 12 likelihood that the clump is a chance grouping).

We investigate the relative probability that such clumps of BHB stars occur by chance by means of Monte Carlo simulations represented by a smooth density law falling off as $\rho \sim r^{-3.5}$, where r is galactocentric distance. We assume the simulations mimic the Sirko et al. (2004) data. Therefore the simulations contain: the same number of stars, velocity dispersion and volume, i.e. we assume there are 703 BHB stars with g < 18, and a velocity dispersion $\sigma = 101$ kms^{-1} contained within the Sirko et al. (2004) area. We also assume the BHB stars each have exactly the same absolute magnitude. We recover clumps in the simulations using the SPS method outlined in §2. The results of 1000 such Monte Carlo simulations reveal that the expected number of simulated clumps in one realization is four and that more than 99% of the simulations contain seven clumps or less. The most likely number of stars contained in a clump is also four although clumps can contain considerably more stars than this; around 90% of the clusters contain eight members or less.

It is clear, therefore, that with the survey material at our disposal, the discovery of clumps in the BHB star distribution can only be a necessary first step; *establishing the reality of these clumps needs additional evidence*. With these limitations in mind, we now apply these techniques to the $g \leqslant 18$ sample of BHB stars reported in Sirko et al. (2004) in our search for sub-structure in the halo.

3   RESULTS

The SPS technique yielded *eight* clumps of BHB stars that contain *four* or more members. Table 1 gives the positions and other data for these clumps candidates whose space den-

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[1] We use the convention with X positive towards the Galactic Centre used by Harris, 1996.

Clump	RA h m	Dec. ° ′	l °	b °	$\langle D \rangle$ [kpc]	$\langle R_{gal} \rangle$ [kpc]	N_{bhb}	$\langle R \rangle$ [kpc]	$\rho_{1.5}$ [kpc^{-3}]	$\langle \nu_{los} \rangle$ [kms^{-1}]	$L_{2.0}$
1	16:14	+36:49	59.4	+46.0	7.8	08.9	6	0.8	0.3 ± 0.1	+39 ± 4	0.40
2	01:19	00:00	137.9	−62.0	31.6	35.2	8	1.8	0.2 ± 0.0	−36 ± 6	0.82
3	15:33	+01:13	006.0	+43.3	08.4	06.1	4	0.9	0.3 ± 0.1	+74 ± 4	0.98
4	14:51	-00:39	354.7	+50.8	09.5	07.7	6	1.3	0.3 ± 0.1	−17 ± 6	0.20
5	15:27	+46:31	075.8	+53.6	12.1	13.5	5	1.1	0.4 ± 0.1	−09 ± 5	0.96
6	09:53	+05:24	231.8	+42.3	09.6	15.1	4	0.8	0.3 ± 0.1	+74 ± 7	0.11
7	23:42	−00:32	088.4	+58.3	07.7	11.0	4	0.8	0.3 ± 0.1	−88 ± 5	0.08
8	00:08	+00:04	100.5	−60.5	15.2	17.8	4	0.9	0.3 ± 0.1	−54 ± 5	0.02

Table 1. Clump candidates defined by BHB stars. The RA and Dec. are for J2000. $\langle D \rangle$ & $\langle R_{gal} \rangle$ are the mean heliocentric and galactocentric distances respectively. N_{bhb} is the number of BHB stars in each clump and $\langle R \rangle$ is their mean distance from the clump centroid. Finally, $\langle \nu_{los} \rangle$ is the mean galactocentric radial velocity of the clumps. $L_{2.0}$ is defined in the text

Sirko no.	$X_\odot$ [kpc]	$Y_\odot$ [kpc]	$Z_\odot$ [kpc]	R [kpc]	$V_\odot$ [kms^{-1}]	ν_{los} [kms^{-1}]	g_0	$(g-r)_0$	$(u-g)_0$	μ_α [mas/yr]	μ_δ [mas/yr]
					Clump One						
959	2.0	4.4	5.9	0.9	−100	+038	14.98	−0.11	1.12	−09	+00
968	2.9	4.7	5.9	0.4	−102	+037	15.12	−0.19	1.11	−07	−01
972	3.2	4.8	5.5	0.5	−110	+034	15.05	−0.21	1.16	−08	−01
995	2.4	4.7	4.9	0.7	−105	+049	14.85	−0.17	1.13	−16	+02
1110	1.8	4.5	5.7	1.0	−092	+051	14.95	−0.16	1.11	−04	+01
1167	4.3	4.3	5.5	1.5	−106	+023	15.15	−0.25	1.14	−08	−02
Mean	2.8	4.6	5.6			+39 ±4					
					Clump Two						
548	−10.2	10.4	−28.3	0.9	−090	−26	18.06	−0.15	1.21	...	...
552	−10.2	9.0	−25.4	2.8	−125	−65	17.85	−0.15	1.18	...	...
553	−10.9	10.0	−28.7	0.8	−074	−14	18.10	−0.27	1.20	...	...
556	−11.1	10.4	−29.3	1.5	−086	−24	18.16	−0.24	1.20	...	...
557	−10.3	10.0	−26.8	1.2	−110	−46	17.97	−0.10	1.20	...	...
559	−12.5	10.0	−30.6	3.2	−088	−33	18.29	−0.23	1.09	...	...
562	−10.7	9.4	−25.4	2.6	−113	−51	17.87	−0.13	1.21	...	...
565	−12.1	10.3	−28.9	1.6	−094	−33	18.14	−0.17	1.20	...	...
Mean	−11.0	10.0	−28			−36 ± 6					
					Clump Three						
411	5.2	0.3	6.3	1.1	063	082	15.17	−0.27	1.10	−11	−18
413	6.7	1.2	6.0	0.9	038	079	15.35	−0.20	1.18	...	...
845	6.6	0.6	5.8	0.6	037	064	15.40	−0.27	1.00	−07	−02
847	5.5	0.6	4.8	1.0	040	070	15.00	−0.23	1.00	−16	−12
Mean	6.0	0.7	5.7			74 ± 4					
					Clump Four						
337	5.7	−0.5	8.0	0.7	−040	−040	15.55	−0.24	1.13	+01	−10
388	4.7	−1.3	8.4	1.9	−003	−022	15.51	−0.07	1.21	−15	−05
408	5.1	−0.1	6.5	1.3	−020	−010	15.31	−0.18	1.16	−06	−16
812	6.0	−1.3	7.4	0.8	+003	−015	15.69	−0.29	0.90	...	...
833	7.4	−0.2	7.1	1.5	−007	+002	15.69	−0.21	1.03	...	...
837*	6.6	+0.3	6.4	1.4	−036	−017	15.48	−0.26	1.00	−07	−6
Mean	5.9	−0.5	7.3			−17 ± 6					

Table 2. Properties of the individual BHB stars in clumps one to four summarized in Table 1. $X_\odot$,$Y_\odot$ & $Y_\odot$ and $V_\odot$ are the heliocentric coordinates and velocities of the stars. Also listed are the de-reddened colours $(g-r)_0$, $(u-g)_0$ and magnitude g_0. * The proper motion of this star is taken from the ACR Catalog around the Celestial Equator (Stone et al., 1999).

Clump	$X_\odot$ [kpc]	$Y_\odot$ [kpc]	$Z_\odot$ [kpc]	$\Lambda_\odot$ °	$B_\odot$ °	N_1	N_2
1	−04.98	−04.93	+07.37	224.68	−46.46	0	0
2	−19.99	−33.12	+05.19	121.12	−07.65	0	0
3	−04.02	−03.92	+02.05	224.24	−20.02	13	1
4	−03.69	−05.84	+01.54	237.71	−12.57	16	3
5	−06.01	−08.66	+10.83	235.21	−45.77	0	0
6	−15.92	−11.65	−04.80	216.19	−13.67	0	0
7	−07.94	−07.60	+08.64	223.75	−38.17	34	0
8	−09.51	−17.24	+05.76	118.89	−16.31	5	2

Table 3. Relation of clumps to the Sgr stream (Majewski et al. 2003). $X_\odot$, $Y_\odot$ & $Y_\odot$ are the rectangular heliocentric coordinates. $\Lambda_\odot$ and $B_\odot$ are defined in the text. N_1 is the number of M-giants (Majewski et al. 2004) that lie within 3.5 kpc of the centroid of the clump and N_2 is the number of these whose ν_{los} lies within 15 km/s of the $\langle \nu_{los} \rangle$ of the clump.

sity (denoted as $\rho_{1.5}$ and defined as the number of stars per cubic kpc within a radius of 1.5 kpc of the mean clump centroid) is greater or comparable with that of the VSS. Additional evidence to support the reality of clumps 1, 2, 3 & 4 is given below; data for the individual BHB stars in these clumps are given in Table 2.

Clump 1: The centroid of this clump is 1.96 kpc from the globular cluster M92. The ν_{hel} of the cluster and clump are +58 and +39 km/s respectively. The clump is unlikely to be bound to M92 as there is a differential velocity of Δ V = 19 km/s and it would take $\sim 10^8$ years for BHB stars to travel the $\sim$ 2 kpc from the cluster center. It is possible that the BHB stars were tidally stripped from the cluster during a recent passage by a stronger Galactic gravitational field. Leon, Meylan & Combes (2000) find evidence for such tidal stripping for 20 globular clusters which can span huge distances (e.g. Grillmair & Johnson 2006). Indeed, there is some evidence that M92 is also being tidally stripped of stars: Yee et al. (2003) have reported a marginal elongation in the NE to SW direction; the clump lies to the SW of the cluster.

Clump 2: This clump of eight stars is contiguous with a clump of four BHB stars discovered by Arnold & Gilmore (1992). These authors claim that the stars are not bound to each other but may be the stellar remnant of a recently disrupted halo cluster. The centroid of their clump is at $X_\odot$ = −9.1. $Y_\odot$ = +11.5 and $Z_\odot$ = −29.4 kpc (2.9 kpc from that of our clump 2) and has a $\langle \nu_{los} \rangle$ of −74 km/s and a standard error of $\sim$5 km/s. Such streams of stars can be seen as gradients in the galactocentric velocity (e.g. Majewski et al., 2004; Clewley & Jarvis, 2006). Figure 2 plots the V_{gal} versus RA for the eight BHB stars in clump 2 and the stars that were found to be in a clump by Arnold & Gilmore (1992). The paucity of the data and the large velocity errors make this stream detection speculative. Clearly, the observation of a larger sample of BHB stars along this putative stream is required to confirm its reality.

Clump 3: The centroid of this clump is 1.0 kpc (17 tidal radii) from the Oosterhoff type 1 globular cluster M5; its $\langle \nu_{los} \rangle$ of +74 km/s is the same as that of the cluster (+75 km/s). Eight RR Lyrae stars (QUEST 392, 408, 418, 423, 426, 429, 436, and 456 (Vivas et al. 2004) lie within 1.5 kpc of the centroid of this clump. The period distribution of the type *ab* RR Lyraes in this group is consistent with their belonging to Oosterhoff type 1.
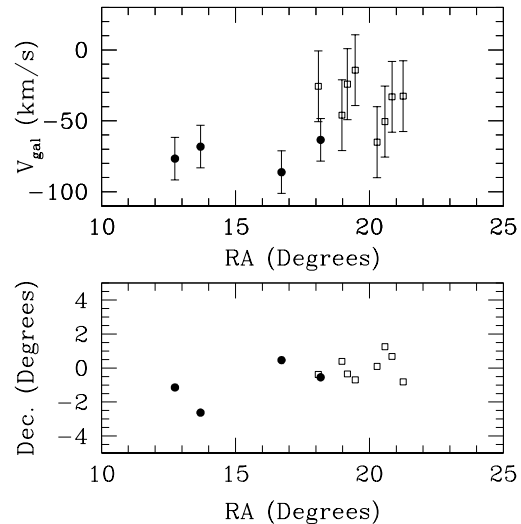

Figure 2. *Upper:* Plot of V_{gal} versus RA for the eight BHB stars in clump 2 (open squares) and four BHB stars found to be in a clump by Arnold & Gilmore (1992). *Lower:* A plot of RA versus Dec. for the BHB stars.

Clump 4: Five RR Lyrae stars (QUEST 331, 341, 365, 376 and 386 lie within 1.5 kpc of the centroid of this clump. Three M giants (1411221-061013, 1428255-082436 and 1434332-0140570) with ν_{los} of −16.8, −40.5 and −7 km/s respectively (Majewski et al., 2004) lie within 3.5 kpc of the centroid of this clump. An association with the Sgr tidal stream (described below) seems likely.

Of the four clumps that have additional observational evidence we consider clump 4 to be the most convincing with clumps 1,2 and 3 requiring either additional or more accurate observational data. In an attempt to find such evidence we also investigate the use of available proper motion data for the clumps. Such proper motions - taken predominantly from the Second US Naval Observatory CCD Astrograph Catalog (UCAC2) catalogue - are given in Table 2 and are available for the BHB stars in clump 1, 3 and 4. In each clump the dispersion in these proper motions is no more than that to be expected from their likely errors but this only weakly constrains the possible tangential velocities of these stars. In short, the UCAC2 proper motion errors are too large for them to be presently useful in this study.

3.1 The Sgr stream

Many types of halo field stars have been found to be associated with this stream: M-giants (Majewski et al. 2003, 2004; Law et al. 2005), RR Lyrae stars (Ivezić et al. 2000; Vivas et al., 2001; Vivas et al., 2005), BHB stars (Newberg et al., 2002; Clewley et al., 2006), metal-poor K giants (Kundu et al. 2002) and carbon stars (Totten & Irwin, 1998). It is therefore desirable to see if any new clumps are associated with this stream. Majewski et al. (2003) have defined a coordinate system in which the zero plane of the latitude coordinate $B_\odot$ coincides with the best-fit great circle defined by a sample of 1161 M-giants, as seen from the Sun; the longitudinal coordinate $\Lambda_\odot$ is zero in the direction of the Sgr core and increases along the Sgr trailing stream. About 60% of these M-giants lie within 2σ (3.6 kpc) of the plane. The coordinates of our clumps in this system are given in Table 3; only clump 4 seems likely (and clump 3 possibly) to be associated with the Sgr stream.

4 DISCUSSION

The angular diameters of these clumps are comparable with the angular extent of the survey material in which they were found (Fig. 1). Consequently they (and the VSS) must extend over distances of at least a few kpc or more. By comparison, the width of the tidal tails of the globular cluster Pal. 5 studied by Odenkirchen et al. (2003) is only about 200 pc. Vivas et al. (2003) found an overdensity of RR Lyrae stars near Pal. 5 that "extend even farther away from the cluster and over a wider range of directions than the narrow tidal tails". However, Grillmair and Dionatos (2006) have noted that BHB stars do not occur in the directions of this cluster's tidal tail and we can find no compelling evidence for the association of any of our sample of BHB stars with this cluster. The large extension of these clumps is understandable if they are the tidal debris of a dSph galaxy; less so if they come from a globular cluster (as in the case of clumps 1 and 3). Presumably there are red giants associated with clumps 1,3 and 4 that are bright enough for their $[\alpha]/[\text{Fe/H}]$ ratio (an indicator of their progenitor's origins) to be obtainable.

In summary, we have used a simple selection technique to isolate eight clumps of BHB stars. There is some additional evidence to support the reality of four of these clumps. In the case of two of them, the additional presence of an overdensity of RR Lyrae stars makes their reality likely. Further support for the reality of these clumps could come from improved radial velocities since their expected velocity dispersions should be small. Further observations of the radial velocities or proper motions of the stars in the clumps as well as isolating other halo stars in these regions are required to establish the reality and nature of the remaining clumps.

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